SOLAR/2002-78/14

SOLAR ENERGY SYSTEM PERFORMANCE EVALUATION

RADIAN CORPORATION OFFICE BUILDING
AUSTIN, TEXAS
SEPTEMBER 1977 THROUGH MAY 1978

July 1978

Contract EG-77-C-01-4049

United States Department of Energy

National Solar Heating and
Cooling Demonstration Program

National Solar Data Program

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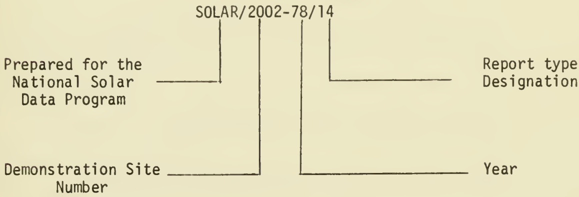
TABLE OF CONTENTS

NATIONAL SOLAR DATA PROGRAM REPORTS

Reports prepared for the National Solar Data Program are numbered under a specific format. For example, this report for the Radian Corporation project site is designated as SOLAR/2002-78/14. The elements of this designation are explained in the following illustration:



- o Demonstration Site Number:

  Each project site has its own discrete number - 1000 through 1999 for residential sites and 2000 through 2999 for commercial sites.

- o Report Type Designation:

  This number identifies the type of report, e.g.,

  - Monthly Performance Reports are designated by the numbers 01 (for January) through 12 (for December)
  - Solar Energy System Performance Evaluations are designated by the number 14.
  - Solar Project Descriptions are designated by the number 50
  - Solar Project Cost Reports are designated by the number 60

These reports are disseminated through the U. S. Department of Energy, Technical Information Center, P. O. Box 62, Oak Ridge, Tennessee 37830.

LIST OF FIGURES AND TABLES

1. FOREWORD

The National Program for Solar Heating and Cooling is being conducted by the Department of Energy in accordance with the Solar Heating and Cooling Demonstration Act of 1974. The overall goal of this activity is to assist in establishment of a viable solar energy industry and to stimulate its growth so as to achieve a substantial reduction in fossil fuel consumption through widespread use of solar heating and cooling applications. The International Business Machines Corporation is contributing to this overall goal by monitoring, analyzing, and reporting system performance of solar energy systems through the National Solar Data Program. Information gathered through the Demonstration Program is disseminated in a series of site-specific reports. These reports are issued as appropriate and may include topics such as:

- Solar Project Description
- Design/Construction Report
- Project Costs
- Maintenance and Reliability
- Operational Experience
- System Performance Evaluation

All reports issued during this report period by the National Solar Data Program for the Radian Corporation solar energy system are listed in Section 5, References. Also presented is information on how to order these reports.

This System Performance Evaluation report is a product of the National Solar Data Program. Evaluation reports are periodically issued to document results from analysis of a specific solar energy system's operational performance during the period covered by the report. The information presented in this report has been extracted or generated from monthly performance data collected at the specific site. These data include system description, operational characteristics and capabilities as well as the results of the evaluation of actual performance. Each parametric value presented as characteristic of this system's performance represents over eight thousand discrete measurements obtained monthly through the National Solar Data Network.

Acknowledgments are extended to the personnel of the Radian Corporation for their cooperation in the collection and analysis of their solar energy system's performance data and for their helpful insight in the preparation of this report.

2. SUMMARY AND CONCLUSIONS

This System Performance Evaluation report presents a summary of the September 1977 to May 1978 operation of the Radian Corporation solar energy system. This system is designed to provide space heating and cooling for approximately 700 square feet of office and laboratory area in an Austin, Texas office building. Presented are results of an evaluation of measured system performance and a comparison of measured micrometeorological data with long term average conditions. Performance evaluations of each major subsystem are also presented.

Measurement data used [1-8]* were collected through the National Solar Network [9] for the period September 1977 through May 1978. As measurement data were not available for November 1977, November climatic conditions have been estimated and are so indicated where used in this study. System performance data are provided through the National Solar Data Network via the IBM developed Central Data Processing System [10]. The Central Data Processing System supports the daily collection and analysis of data from instrumented solar energy systems located throughout the country. These data are summarized into monthly performance reports which form the common basis used for system evaluation.

This report includes: a brief system description, review of actual system performance during the report period, analysis of performance based on evaluation of climatic, load and operational conditions, and an overall discussion of the results of analysis. Also presented are results of a special study of the Radian collector array subsystem.

Measured monthly values of AMBIENT TEMPERATURE** during the nine month report period were slightly cooler than normal with the measured average AMBIENT TEMPERATURE 62°F vs. the long term average for the same period of 63°F. Ranges of daily average values of AMBIENT TEMPERATURE were greater than normal. This resulted in both a greater number of measured Heating Degree Days*** (2065 vs. 1737) and Cooling Degree Days (1336 vs. 1191) than the long term average. The average monthly incident solar energy per unit area measured during the report period (at a 30° tilt) was 45769 Btu/Sq. Ft. This was less than the estimated normal for the same nine month period of 50562 Btu/Sq. Ft. and the estimated yearly average of 53461 Btu/Sq. Ft. These estimates are for a south facing surface tilted at 30° to horizontal and located in Austin, Texas.

During the periods September and October 1977 and December 1977 through May 1978, the solar energy system at Radian provided 1.63 million Btu of the 12 million Btu demand for space heating. During this time, the solar energy system provided

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* Numbers in brackets designate References listed in Section 5.

** Terms in all capitals are formal names of specific performance factors used in the National Solar Data Program and as defined in References 14 and 15.

*** Terms with first letter capitals are other than the specific performance factors defined.

none of the 46.2 million Btu demand for space cooling. This measured performance of the solar energy system was less than that expected based on the performance evaluation summarized in Section 4 and the meterological conditions summarized above. Primary reasons for this level of performance are problems attributed to the collector array tracking mechanism throughout the report period and excessive energy losses from the storage tank prior to January 1978. These conditions combined to hinder the effectiveness of the system in providing space heating and to prevent the solar energy system from providing any of the required space cooling.

3. SYSTEM DESCRIPTION SUMMARY

The following is a brief summary of the Radian Corporation Office Building solar installation. For detailed system description see Reference 11. Highlights of this site include:

- o COLLECTOR TYPE: Concentrating, Liquid, Tracking
- o FREEZE PROTECTION: Antifreeze
- o APPLICATION: Heating, Cooling
- o STORAGE TYPE: Exterior Tank
- o NEW OR RETROFIT: Retrofit
- o INSTRUMENTED FOR PERFORMANCE EVALUATION: Yes

The solar energy system heats and cools approximately 800 square feet of office and laboratory area in this two story, modern office building in Austin, Texas. Though intended to be installed as the building was constructed, the system was actually installed when the building was essentially complete and, thus, must be considered a retrofit installation.

The system utilizes 36 Northrup concentrating collectors which provide an effective aperture area of 350 square feet and a total collector area of 360 square feet. The collectors are ganged in two banks on the flat roof of the building. An aluminum angle support structure tilts the collectors toward the south and the collectors track the sun from east to west through the day. A tracking mechanism is provided for each of the two banks of collectors. The gross collector array area is 1380 square feet.

The collectors in each bank are connected in parallel with hoses and clamps to the copper manifolds. A water/glycol mixture is pumped from the collectors to a counter flow heat exchanger between the collectors and the storage tank. The 1500 gallon insulated, fiberglass storage tank is located above ground on a concrete pad near the building.

All but one of the pumps for the system are located outside the building near the tank and are covered with individual galvanized sheet metal housing. The other pump is located near the chiller. All exterior piping is insulated with fiberglass covered by an aluminum jacket.

The cooling equipment for the system is an Arkla 3-ton packaged absorption air-cooler located on the second floor of the building and a cooling tower on the roof. A separate heating coil, through which solar heated water from the storage tank is circulated, is provided in the Arkla unit for space heating.

Auxiliary heating and cooling to the three solar conditioned rooms is provided through a completely separate duct system.

The solar system has been fully instrumented for data acquisition and is included in the National Solar Data Network.

The collector to storage system is shown schematically in Figure III-1. The storage to load system is presented in Figure III-2. The system has seven modes of operation. These modes are described below:

Mode 1 - Energy Collection and Storage: During this mode of operation, water is pumped from the 1500 gallon storage tank through the collectors and back. This mode is initiated whenever the collector absorber plate temperature exceeds the temperature of the bottom of storage by 10°F.

Mode 2 - Solar Heating: This mode is activated whenever the building thermostat calls for heating and the average temperature of the storage tank exceeds the minimum temperature of 100°F. Water is pumped from storage to a heat exchanger located in the air distribution system of the building.

Mode 3 - Solar Cooling: This mode is activated whenever the building calls for cooling and the average temperature of the storage tank exceeds 180°F, the minimum needed to activate the absorption cycle of the solar air conditioner.

Mode 4 - Auxiliary Heating: Whenever the temperature of the storage tank is below 100°F and no useful solar energy is available, all space heating is provided by a natural gas fired furnance.

Mode 5 - Auxiliary Cooling: Whenever the temperature of storage is below the minimum temperature necessary to activate the absorption cycle of the solar powered air conditioner, space cooling is provided by a conventional vapor compression air conditioner.

Mode 6 - Solar & Auxiliary Heating: Whenever the space heating load cannot be met entirely by solar energy, the auxiliary heating will operate in conjunction with the solar heating system.

Mode 7 - Solar & Auxiliary Cooling: Whenever the space cooling load cannot be met entirely by solar energy, the auxiliary heating will operate in conjunction with the solar cooling system.

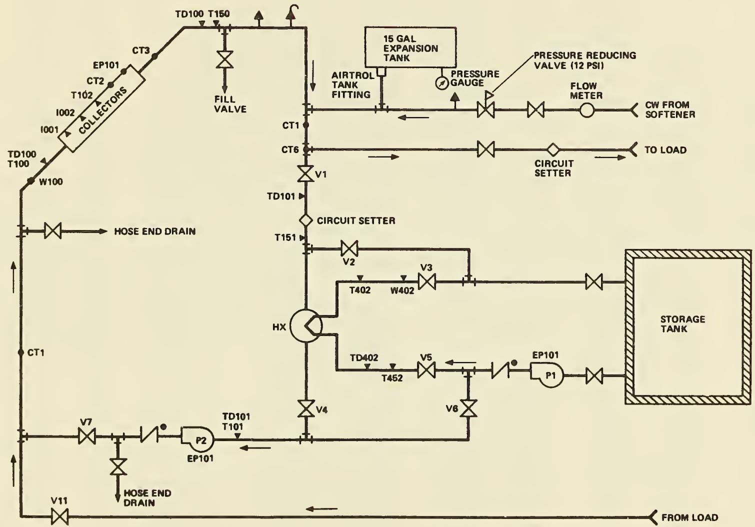


Figure III-1. Radian System Schematic Collector to Storage

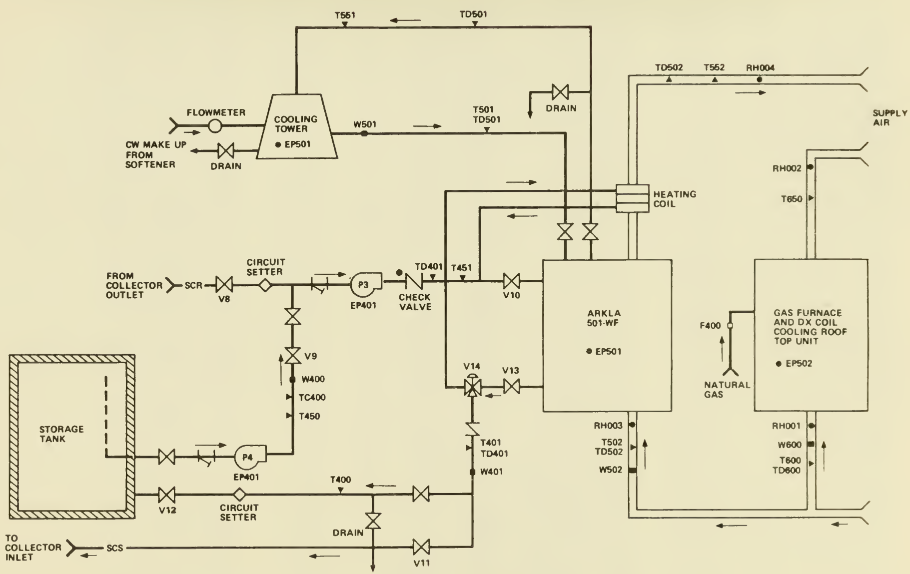


Figure III-2. Radian System Schematic Storage to Loads

4. PERFORMANCE EVALUATION

Measured solar energy system performance is provided by the CDPS through computation of solar energy performance factors. These computations are based on the intergovernmental agency report "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program" [14]. Because all solar energy systems are not identical, standard instrumentation equipment and software used in data processing is adapted to each system. The approach provides a standardized set of performance evaluation parameters for each solar system under consideration.

The National Solar Data Network equipment collects measurement data from each site and stores it in an on-site memory. The data are retrived periodically and stored on a master data base. They are then used to compute the primary performance factors.

Converted and tested data are first subjected to an hourly evaluation process. This process obtains all measurements for a particular hour, and performs the computations necessary to determine the hourly performance parameters. These hourly calculations form the basis for subsequent daily and monthly system performance evaluation. Definitions of the evaluation parameters are provided in Appendix A. The hourly performance equations used for the Radian system are listed in Appendix B.

Monthly performance reports are generated to represent subsystem and total system performance. Monthly system summary reports are accompanied by a set of subsystem summaries which prove a record of performance for each day of the month. These monthly reports are the baseline for actual system performance used in the comparisons presented in the subsequent sections of this report.

4.1 Meteorological and Load Conditions

Monthly values of INCIDENT SOLAR ENERGY PER UNIT AREA (total incident solar energy measured in the plane of the collector array), AMBIENT TEMPERATURE (average outdoor temperature at the site), Heating Degree Days and Cooling Degree Days measured at the Radian site during the report period are presented in Table IV-1.

Monthly values of Heating and Cooling Degree Days are derived from daily values of AMBIENT TEMPERATURE as they are useful indications of the system's heating and cooling demand respectively. Heating Degree Days and Cooling Degree Days are computed when the daily average temperature falls below or rises above 65°F. If the daily average temperature is 60°F, then 5 Heating Degree Days have accumulated. Likewise, if a day's average temperature was 80°F, then 15 Cooling Degree Days have accumulated. Daily values of Heating and Cooling Degree Days are each summed monthly.

Also presented in Table IV-1 are long term average (normal) monthly values for the meteorological parameters described above. Data for long term INCIDENT SOLAR ENERGY PER UNIT AREA are estimates based on the Climatic Atlas of the United States [12]. These estimates us the Austin, Texas horizontal data given in the reference to provide average values for the 30° tilt angle of the south facing Radian collector array. The estimation procedure used is detailed in Reference 16. All other long term average climatic data were taken from the National Oceanic and Atmospheric Administration summary [13] for Austin, Texas. Long term averages are also presented for an entire year to facilitate comparison.

INCIDENT SOLAR ENERGY (total solar energy incident on the gross collector array area) for the Radian site was less than average six of the eight months reported. The exceptions were December 1977 and March 1978. The average amount measured was 91% of normal for this period. January 1978 has the lowest percentage with 63% of the normal January INCIDENT SOLAR ENERGY.

AMBIENT TEMPERATURE was slightly above normal for September through December 1977. It was lower than normal for January through March and higher again for April and May 1978. The average for the entire report period was 62°F versus the 63°F normal average for the same period.

SPACE HEATING LOAD (the sum of all energy supplied by both solar and auxiliary subsystems) would be expected to have been slightly less than average through December 1977, and greater than average for January through May 1978. This evaluation is based on the measured Heating Degree Days which average 19% higher than normal for the report period. SPACE COOLING LOAD (total energy sensible and latent, removed from the air in the space-cooled area) would be expected to have been greater during the last of 1977 and slightly greater during the first of 1978. The measured Cooling Degree Days averaged 12% greater than normal during the report period.

TABLE IV-1
Climatic Conditions

	INCIDENT SOLAR ENERGY PER UNIT AREA (30°TILT),Btu/Ft^2		AMBIENT TEMPERATURE,°F		Heating Degree Days		Cooling Degree Days	
Month (Year) (1)	Measured (2)	Long Term Average (3)	Measured (2)	Long Term Average (4)	Measured (1)	Long Term Average (4)	Measured (1)	Long Term Average (4)
Jan 78	27933	44056	41	49.7	729	483	7	8
Feb 78	35499	44805	43	53.3	589	344	5	16
Mar 78	53767	53528	58	59.5	235	223	18	52
Apr 78	49812	50444	69	68.6	16	44	140	152
May 78	49148	56611	77	75.2	10	0	391	316
Jun -	-	59500	-	81.6	-	0	-	498
Jul -	-	63167	-	84.6	-	0	-	608
Aug -	-	63806	-	84.7	-	0	-	611
Sep 77	55395	59833	82	78.9	0	0	503	417
Oct 77	51143	56778	71	70.1	10	39	214	197
Nov 77	(45825)*	46667	(61)*	59.1	(154)*	205	(41)*	28
Dec 77	43402	42333	55	52.3	322	399	17	5
Avg. for Report Period	45769	50562	62	63.0	229	193	148	132
Total for Report Period	411924	455055	-	-	2065	1737	1336	1191

NOTE:

1. Measured data covers the period September 1977 through May 1978
2. Values for this parameter obtained through National Solar Data Network
3. Values for this parameter estimated from data presented in Reference 12 for Austin, Texas
4. Values for this parameter obtained from Reference 13 for Austin, Texas

* Indicates estimated values based on other measurements

4.2 System Performance

The overall system performance of a solar energy system can be characterized by its thermal performance, the amount of operating energy required to obtain that performance, and its availability when conditions required it to operate. Thermal performance can be represented by the performance factor TOTAL SOLAR ENERGY USED (the sum of all solar energy supplied to the subsystems). Performance of the collector array, storage, space heating and space cooling subsystems is described in Sections 4.3 through 4.6 respectively. Operating energy required is described in Section 4.7 and system availability is discussed in Section 4.8. The energy savings provided by the system is discussed in Section 4.9.

The Radian solar energy system thermal performance for the period September 1977 through May 1978 is summarized in Table IV-2. All of the solar energy utilized was supplied to the space heating subsystem. Reference to Table IV-5 shows that this represents approximately 14% of that subsystem's thermal demand during this period. None of the thermal requirements of the cooling subsystem were supplied during this report period.

Early in this reporting period when the cooling demand was proportionately much larger than that for heating, an effort was made to utilize the collecting system to increase the storage tank temperature to a level sufficient to operate the absorption cycle air conditioning equipment. Table IV-4 shows that the monthly average storage temperature never reached the 180°F level needed for this operation. The maximum daily storage tank temperature recorded during the report period was 158°F on October 21, 1977. This attempt to raise the storage to a higher temperature was hindered by leaking city water make-up flow into the storage tank. This caused storage to overflow and resulted in a unexpected loss of stored energy. This leak was repaired in early December. However, by this time the primary demand was for space heating and the decision had been made to use storage for space heating for the remainder of the heating season. When cooling demand began to increase in the spring of 1978, an attempt was again made to raise storage temperature to the minimum levels demanded by the absorption cycle air conditioner. The daily average storage tank temperature reached a maximum of 157°F on April 25. The following day a major collector tracking failure ocurred and no further collection of solar energy was attempted during this reporting period.

The overall thermal performance of the Radian solar energy system was the providing of 1.6 million Btu of the 12 million Btu space heating demand and none of the 46 million Btu space cooling demand during the months when data were collected (i.e. all except November 1977). This 1.6 million Btu was provided with the system requiring an amount of solar ENERGY COLLECTION AND STORAGE SUBSYSTEM OPERATING ENERGY (the electrical operating energy required to support the ECSS heat transfer loops) equivalent to 2.0 million Btu as may be seen in Table IV-7. The net result for the Radian Solar Energy system during the report period was the loss of 0.3 million Btu, representing 20% of the solar energy used.

The availability of the Radian solar energy system is discussed in Section 4.8 and summarized in Table IV-8. The lack of availability of the solar energy system at Radian may be primarily attributed to problems with the collector tracking mechanism. The 55% availability of the energy collection and storage subsystem is the prime factor in this entire system problems. Despite the apparent total unavailability of the cooling subsystem, this is directly traceable to the collector tracker failure which precluded the raising of average storage tank temperatures to the 180°F levels sufficient to make operation of the solar powered equipment possible. During the months when a non-trivial heating load was encountered, heating subsystem availability ranged between 10% and 60%. This is once again traceable to the low temperature of solar storage and is related to the collector tracking problem.

Energy Savings are discussed in detail in Section 4.9 and summarized in Table IV-9. During the report period, a total net saving of energy of 0.03 million Btu has resulted. This saving figure includes not only the energy to meet the building load demands, but also the operating energy needed to collect and store the solar energy and to deliver it to the various subsystems. These savings could have been increased substantially had any of the cooling load been met by the solar equipment, for the cooling load was approximately four times the heating load over the report period.

TABLE IV-2

System Thermal Performance

Month	SOLAR ENERGY USED-HEATING Btu (1)	SOLAR ENERGY USED-COOLING Btu (1)	SOLAR ENERGY USED-TOTAL Btu (1)
Sep 77	0	0	0
Oct 77	0.01×10^6 Btu	0	0.01×10^6 Btu
Nov 77	Not Reported	Not Reported	Not Reported
Dec 77	0.05×10^6 Btu	0	0.05×10^6 Btu
Jan 78	0.37×10^6 Btu	0	0.37×10^6 Btu
Feb 78	0.09×10^6 Btu	0	0.09×10^6 Btu
Mar 78	0.84×10^6 Btu	0	0.84×10^6 Btu
Apr 78	0.27×10^6 Btu	0	0.27×10^6 Btu
May 78	0	0	0

NOTE:

1. Values for this parameter obtained through National Solar Data Network

4.3 Collector Array Subsystem

Collector array performance is described by comparison of INCIDENT SOLAR ENERGY (total solar energy incident on the gross collector array area) with COLLECTED SOLAR ENERGY (thermal energy removed from the collector array by the energy transport medium). The ratio of these represents the COLLECTOR ARRAY EFFICIENCY (the ratio of energy collected to total solar energy incident on the collector array). Measured monthly values of INCIDENT SOLAR ENERGY, COLLECTED SOLAR ENERGY, and COLLECTOR ARRAY EFFICIENCY ARE PRESENTED IN Table IV-3.

Evaluation of collector efficiency using OPERATIONAL INCIDENT ENERGY (amount of solar energy incident on the gross collector array area during the time when the collector loop is active) and compensating for the difference between gross collector array area and the gross collector aperture area yields the Operational Collector Efficiency.

Operational Collector Efficiency =

$$\frac{\text{COLLECTED SOLAR ENERGY}}{\text{OPERATIONAL SOLAR ENERGY} \times \left(\dfrac{\text{total collector area}}{\text{gross collector array area}}\right)}$$

where total collector area is the number of collectors multiplied by the gross collector area (as defined by ASHRAE Standard 93-77 [11]) of one collector, and the gross collector array area is the total area of the entire collector array including the framework which is an integral part of the collector structure. For Radian, the total collector area is 360 square feet and the gross collector array area is 1380 square feet.

Operational Collector Efficiency is not precisely the same collector efficiency as represented by ASHRAE Standard 93-77. Both Operational Collector Efficiency and the ASHRAE collector efficiency are defined as the ratio of actual useful energy collected to solar energy incident upon the collector and both use the same definition of collector area. However, the ASHRAE efficiency is determined from instantaneous evaluation under tightly controlled, steady state test conditions, while the Operational Collector Efficiency is determined from the actual conditions of all-day solar energy system operation. Measured monthly values of OPERATIONAL INCIDENT ENERGY and computed values of Operational Collector Efficiency are also presented in Table IV-3.

The average Operational Collector Efficiency of the collector array during the report period was 19%. This efficiency did not significantly change during the September to April period except for January 1978, when it was 29%. The reason for this comparative improvement is not known. However, the collector array experienced problems with the tracking mechanism throughout the report period. As Radian personnel provided maintanence to the collector array subsystem frequently, there could have been some extra efforts made during January. This possibility of a healthier than usual collector array is supported by comparison of the ratio of monthly values of OPERATIONAL INCIDENT ENERGY to

INCIDENT SOLAR ENERGY. This comparison, along with review of the System Availability data presented in Section 4.8, indicates that although the collectors were not operational as much of the time in January as in some other months, January was still the month they collected the greatest percentage of INCIDENT SOLAR ENERGY. This comparison indicates that the collectors were doing a better job during January than in any other month.

All collection of solar energy was halted on April 26, 1978 when a major failure of the tracking mechanism occured. Radian technical personnel have indicated that a later model tracking system has been ordered. This had not been received by the end of May and no operation of the collector array subsystem was attempted during the month.

Discussions with Radian personnel have indicated that the probable cause for the reduced level of performance of the collector array during the report period was frequent tracking system failures. It is believed that these failures were the result of frequent operation of the tracking motors while attempting to correct pointing errors caused by wind loading. The performance of concentrating collectors is highly dependent upon their ability to properly focus the incoming solar energy. This places a great importance on correct pointing of each collector in the array. In addition to difficulty in meeting the basic requirement for tracking the sun with the tracking system, the interconnection of the 36 collectors to ensure that they all tracked together was also indicated as a continual source of concern. Radian personnel performed periodic adjustment on the collector tracking system in an attempt to compensate for slippages in the linking interconnections between collectors. Less than optimal pointing of the collectors is indicated by the average temperature gain across the collector array of 3-5°F. The original system design [20] indicated an expected temperature gain of 10°F across the array.

Tracking problems have been the primary reason that the Radian energy collection and storage subsystem had an average availability of only 55% for the report period. This availability factor represents the fraction of time during which solar energy was available, a demand for solar energy existed, and the system was able to collect and store energy. This also had a detrimental effect on the overall System Availability.

Results of a study of the Radian collector array to determine how specific climatic conditions encountered during the period December 1, 1977 through mid-March 1978 effected collector performance are summarized in Appendix C. These results indicate the following: a noticable degradation of performance was caused by wind speeds above 10 miles per hour, the collector array exhibits a higher efficiency in the morning than in the afternoon, and actual transient climatic conditions encountered did not significantly contribute to degraded performance over more steady-state conditions. These findings are of importance to this report. Although solar energy collector performance is known to be sensitive to wind, the magnitude of this effect for the Radian system was not known. The morning effect appears to be related to the tracking problems previously mentioned, and the lack of sensitivity to transient climatic conditions emphasizes the probability of collector array operational problems as the primary

reason for the performance reported. It should also be noted that wind effect can include both the result of physically stressing the collector tracking system by the wind impact upon the collectors and also by increasing the collector array convective heat loss to the ambient. The relative magnitude of these possible wind effects has not been determined.

TABLE IV-3
Collector Array Performance

Month	INCIDENT SOLAR ENERGY, Btu (1, 3)	COLLECTED SOLAR ENERGY, Btu (1, 3)	COLLECTOR ARRAY EFFICIENCY, Btu/Btu (1, 3)	OPERATIONAL INCIDENT ENERGY, Btu (1, 3)	Operational Collector Efficiency, Btu/Btu (2, 4)
Sep 77	76.4×10^6	1.23×10^6	0.016	27.3×10^6	0.17
Oct 77	70.6×10^6	1.93×10^6	0.026	40.9×10^6	0.18
Nov 77	Not Reported	Not Reported	Not Reported	Not Reported	Not Computed
Dec 77	59.9×10^6	1.5×10^6	0.026	29.4×10^6	0.20
Jan 78	38.5×10^6	1.93×10^6	0.050	25.5×10^6	0.29
Feb 78	50.0×10^6	1.38×10^6	0.028	29.9×10^6	0.18
Mar 78	74.2×10^6	1.70×10^6	0.023	43.8×10^6	0.15
Apr 78	68.7×10^6	1.45×10^6	0.021	29.5×10^6	0.19
May 78	67.8×10^6	0	0	0	Not Computed

NOTE:

1. Values for this parameter obtained through National Solar Data Network
2. Values for this parameter computed from data obtained through National Solar Data Network
3. This parameter is based on gross collector array area
4. This parameter is based on gross collector area

4.4 Storage Subsystem

Storage subsystem performance is described by comparison of ENERGY TO STORAGE (amount of energy delivered to the storage tank), ENERGY FROM STORAGE (amount of energy extracted by the heating and cooling subsystems) and CHANGE IN STORED ENERGY (difference in stored energy from beginning to end of the report period). The ratio of the sum of ENERGY FROM STORAGE and CHANGE IN STORED ENERGY to ENERGY TO STORAGE is defined as STORAGE EFFICIENCY. Measured monthly values of ENERGY TO STORAGE, ENERGY FROM STORAGE, CHANGE IN STORED ENERGY, and STORAGE EFFICIENCY are presented in Table IV-4.

The greatest daily AVERAGE STORAGE TEMPERATURE (average storage tank temperature for the reporting period) during the total report period was 158°F. This temperature was obtained October 21, 1977. Daily values of STORAGE AVERAGE TEMPERATURE are shown for mid-April through May, 1978 in Figure IV-1. Further increase in storage temperature after April 25, 1978, was prevented by a major failure of the collector tracking mechanism on April 26. After this date, the storage tank did not receive any further ENERGY TO STORAGE and thus declined in temperature for the remainder of the report period.

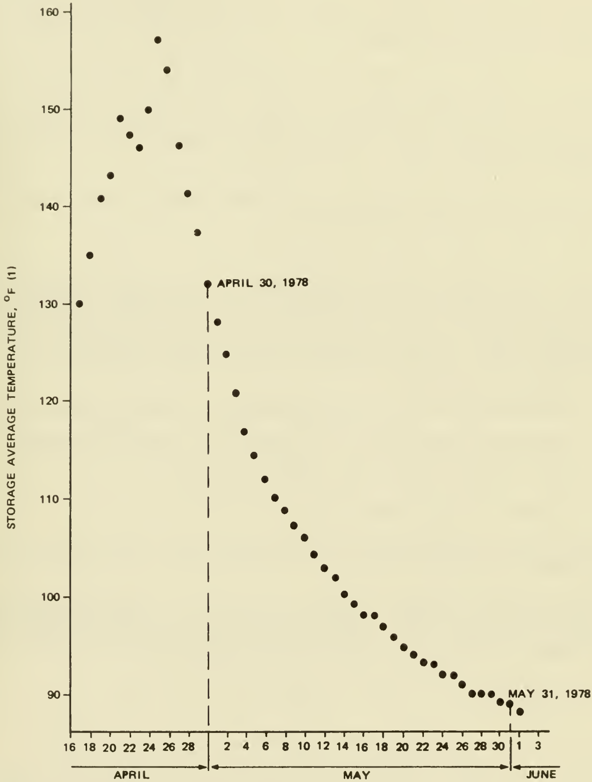
Evaluation of the Radian system storage performance under actual transient system operation and climatic conditions can be performed using the parameters listed above. The utility of these measured data in evaluation of the overall storage design can be illustrated in the derivation presented below.

The design of storage subsystems requires knowledge of insulation properties of the various materials from which the subsystem is to be constructed. This collection of materials (and their various properties) makes the accurate prediction of storage subsystem performance a complex task. The overall thermal properties of the actual storage subsystem design can be derived empirically as a function of STORAGE AVERAGE TEMPERATURE (the mass weighted average temperature of the primary storage medium) and the ambient temperature in the vicinity of the storage tank. For the Radian system, the storage tank is outdoors and the appropriate temperature for the vicinity of the storage tank is AMBIENT TEMPERATURE (average outdoor temperature at the site). An overall heat transfer coefficient for the storage subsystem can be defined as follows:

Effective Storage Heat Loss Coefficient =

$$\frac{(\text{ENERGY TO STORAGE} - \text{ENERGY FROM STORAGE} - \text{CHANGE IN STORED ENERGY})}{((\text{STORAGE AVERAGE TEMPERATURE} - \text{AMBIENT TEMPERATURE}) \times \text{hours in month})}$$

The Effective Storage Heat Loss Coefficient is comparable to the Heat Loss Rate defined in ASHRAE Standard 94-77 [19]. It has been calculated for each month in this report period and included, along with STORAGE AVERAGE TEMPERATURE, in Table IV-4. Examination of these monthly values of heat loss coefficients indicates that values for the first few months reported were almost twice that for the period beginning in January, 1978. Review of the Radian technical personnel activities at the system indicated that a leaking valve was repaired during December, 1977. The effect of this leak had been the continual flow



Note: Values for this Parameters Obtained through NATIONAL SOLAR DATA NETWORK.

Figure IV-1. Storage Average Temperature for period Mid-April through May 1978

of city water into the vented storage tank. This resulted in a constant overflow and thus loss of stored energy via the vent discharge pipe. For those months in which it occurred, this overflow loss was correctly contained in the computed Effective Storage Heat Loss Coefficient. The average value of the coefficient for the report period after the leaking valve was repaired (January through May, 1978) was 26 Btu/hr°F.

An useful application of the Effective Storage Heat Loss Coefficient is the evaluation of storage temperature for periods of time when the amounts of energy delivered to and taken from the tank are equal to each other. Such condition did occur when the Radian system was shut down for extended maintainence from late April through May, 1978. During this period ENERGY TO STORAGE and ENERGY FROM STORAGE were both zero.

For steady state operating conditions, the STORAGE AVERAGE TEMPERATURE at the end of a time period can be determined by:

$$SAT = TA + ((TO - TA) \times EXP(- K \times t))$$

where SAT is the STORAGE AVERAGE TEMPERATURE, TA is the average AMBIENT TEMPERATURE during the time period, TO is the STORAGE AVERAGE TEMPERATURE at the beginning of the time period, K is the ratio of the Effective Storage Heat Loss Coefficient to the thermal capacity of the storage subsystem, and t is the length of the time period in hours. For the 1500 gallon water storage at Radian, TC (the thermal capacity of storage) is:

$$TC = 1500 \text{ gallons} \times 8.34 \text{ (lbs. water/gallon)} \times 1 \text{ (Btu/(lb. water} \times {}^\circ\text{F))}$$

Thus K = (Effective Storage Heat Loss Coefficient) / (Thermal Capacity)

$$= ((20 + 26 + 28 + 29) / 4) / (1500 \times 8.34 \times 1)$$

$$= 2.058 \times 10^{-3} \text{ Bty } {}^\circ\text{F/Btu } {}^\circ\text{F hr}$$

where the Effective Storage Heat Loss Coefficient used is the average for the months January through April 1978.

The STORAGE AVERAGE TEMPERATURE for April 30 was 132°F and the AMBIENT TEMPERATURE for the month of May was 77°F. Measured daily values of STORAGE AVERAGE TEMPERATURE are presented in Figure IV-1. Using the prediction procedure above, the STORAGE AVERAGE TEMPERATURE for May 31 would have been computed as:

$$SAT = 77 + ((132 - 77) \times EXP(- 2.058 \times 10^{-3} \times 24 \times 31))$$
$$= 88.9^\circ F$$

The measured value of STORAGE AVERAGE TEMPERATURE for May 31 was 89°F.

Dimensions of the Radian storage tank were obtained from Reference 11. The indicated total surface area exposed to ambient environment is approximately 188 square feet and the area of the base of the storage tank is 28 square feet. The thickness of the urethane insulation used on the fiberglass tank is 2 inches on the bottom and 3 inches elsewhere. For the average Effective Storage Heat

Loss Coefficient used in the computation above, the average thermal conductivity of the storage tank is 0.137 Btu/hr °F ft2. With an average thickness of insulation of 2.85 inches, this is an overall thermal conductivity of 0.39 Btu/hr °F ft2 in, or approximately three times the conductivity of urethane insulation. This variation in conductivity values emphasizes the utility of system characteristics derived from measured data as a refinement to estimates of performance based solely on design data.

TABLE IV-4
Storage Subsystem Performance

Month	ENERGY TO STORAGE, Btu(1)	ENERGY FROM STORAGE, Btu(1)	CHANGE IN STORED ENERGY, Btu(1)	STORAGE EFFICIENCY, Btu/Btu(1)	STORAGE AVERAGE TEMPERATURE, °F (1)	Effective Storage Heat Loss Coefficient, Btu/Hr°F (2)
Sep 77	1.63×10^6	0	0.51×10^6	.31	110	56
Oct 77	2.52×10^6	0.01×10^6	-0.12×10^6	-.02	140	50
Nov 77	Not Reported	Not Reported	Not Reported	Not Reported	Not Reported	Not Computed
Dec 77	2.34×10^6	0.05×10^6	0.13×10^6	.16	113	46
Jan 78	2.02×10^6	0.37×10^6	-0.34×10^6	.54	103	20
Feb 78	1.74×10^6	0.09×10^6	0.74×10^6	.51	93	26
Mar 78	2.20×10^6	0.84×10^6	-0.14×10^6	.35	128	28
Apr 78	1.60×10^6	0.27×10^6	-0.09×10^6	.16	134	29
May 78	0	0	-0.50×10^6	Infinite	101	28

NOTE:

1. Values for this parameter obtained through National Solar Data Network
2. Values for this parameter computed from data obtained through National Solar Data Network

4.5 Space Heating Subsystem

Space heating subsystem performance is described by comparison of SOLAR ENERGY USED (amount of solar energy supplied to the space heating subsystem) with SPACE HEATING LOAD (the sum of energy supplied by both solar and auxiliary sources). Measured monthly values for these performance factors are presented in Table IV-5.

The space heating subsystem utilizes solar energy stored in the external tank to provide heat by circulation through a heat exchanger in the building's air distribution system. The building thermostat will initially attempt to obtain heating from the solar energy system storage tank. If the temperature of storage is greater than 100°F, solar heated water will be made available. If the storage temperature is less than 100°F, auxiliary heat will be provided by a natural gas fired furnace. Due to the difficulty in collecting energy caused by tracking system problems and the relatively large storage tank energy losses, temperatures in excess of 100°F were frequently not available when required. Overall performance of the system during the heating season was to supply 1.6 million Btu of a required 12 million Btu demand, or approximately 14% of the space heating demand during the reporting period.

TABLE IV-5

Heating Subsystem Performance

Month	SOLAR ENERGY USED-HEATING, Btu(1)	AUXILIARY THERMAL USED, Btu (1)	SPACE HEATING LOAD, Btu (1)
Sep 77	0	0	0
Oct 77	0.01×10^6	0	0.01×10^6
Nov 77	Not Reported	Not Reported	Not Reported
Dec 77	0.05×10^6	0.95×10^6	1.00×10^6
Jan 78	0.37×10^6	3.69×10^6	4.00×10^6
Feb 78	0.09×10^6	5.24×10^6	5.40×10^6
Mar 78	0.84×10^6	0.44×10^6	1.29×10^6
Apr 78	0.27×10^6	0	0.27×10^6
May 78	0	0	0

NOTE:

1. Values for this parameter obtained through National Solar Data Network

4.6 Space Cooling Subsystem

Space cooling subsystem performance is described by comparison of SOLAR ENERGY USED (the amount of solar energy supplied to the space cooling subsystem) and AUXILIARY ELECTRIC FUEL (the amount of electrical energy supplied directly to the subsystem) with SPACE COOLING LOAD (the total energy, latent and sensible, removed from the air in the space cooled area of the building). Measured monthly values for these performance factors are presented in Table IV-6.

The minimum temperature at which the absorption cycle air chiller can be operated is 180°F. At no time during the report period did the temperature of the storage tank reach a temperature high enough to enable the operation of the air chiller. Because of this inability, none of the 46 million Btu cooling load reported was provided by solar energy.

TABLE IV-6

Cooling Subsystem Performance

Month	SOLAR ENERGY USED-COOLING, Btu (1)	AUXILIARY ELECTRICAL FUEL, Btu (1)	SPACE COOLING LOAD, Btu (1)
Sep 77	0	7.11×10^6	14.8×10^6
Oct 77	0	4.33×10^6	9.01×10^6
Nov 77	Not Reported	Not Reported	Not Reported
Dec 77	0	1.58×10^6	3.30×10^6
Jan 78	0	0.68×10^6	1.43×10^6
Feb 78	0	0.66×10^6	1.37×10^6
Mar 78	0	2.10×10^6	4.38×10^6
Apr 78	0	2.26×10^6	4.71×10^6
May 78	0	3.46×10^6	7.21×10^6

NOTE:

1. Values for this parameter obtained through National Solar Data Network

4.7 Operating Energy

Operating energy is defined as the power used to provide for the transport of energy to the point of use. Total operating energy for the solar energy system at Radian consists of ENERGY COLLECTION AND STORAGE SUBSYSTEM OPERATING ENERGY (electrical energy required to support the ECSS heat transfer loops), SPACE HEATING OPERATING ENERGY (electrical energy to support the subsystem, e.g. fans and pumps, not intended to directly effect the thermal state of the subsystem), and SPACE COOLING OPERATING ENERGY (electrical energy to support the subsystem, e.g. fans and pumps, not intended to directly effect the thermal state of the subsystem). Measurements of the monthly values of these performance factors are presented in Table IV-7.

The average monthly operating energy for the months September 1977 through April 1978 was 0.29 million Btu. This provided the electrical power to the collector pumps to collect a monthly average 1.6 million Btu of solar energy. This collected energy is over five times the amount of energy used to operate the collector and storage subsystems.

The operating energy for the cooling subsystem was greater than for the heating subsystem every month except January and February 1978. As both of these include measurements of power used by the same air distribution system, the predominance of the cooling requirements in Austin can be easily seen. The heating subsystem required operating energy equal to approximately 6 percent of the heating load and the cooling subsystem approximately 8 percent of the cooling load. This ratio of operating energies is not as large as the ratio of the cooling to heating load, however, for additional energy is required to operate the solar heating subsystem when solar energy is used to supplement the auxiliary heating source.

TABLE IV-7

System Operating Energy

Month	ECSS OPERATING ENERGY, Btu (1)	SPACE HEATING OPERATING ENERGY Btu (1)	SPACE COOLING OPERATING ENERGY Btu (1)	TOTAL SYSTEM OPERATING ENERGY, Btu (1)
Sep 77	0.20×10^6	0	0	0.20×10^6
Oct 77	0.32×10^6	0	1.08×10^6	1.40×10^6
Nov 77	Not Reported	Not Reported	Not Reported	Not Reported
Dec 77	0.28×10^6	0.04×10^6	0.40×10^6	0.72×10^6
Jan 78	0.25×10^6	0.19×10^6	0.17×10^6	0.61×10^6
Feb 78	0.27×10^6	0.41×10^6	0.16×10^6	0.84×10^6
Mar 78	0.38×10^6	0.04×10^6	0.53×10^6	0.95×10^6
Apr 78	0.33×10^6	0.02×10^6	0.56×10^6	0.91×10^6
May 78	0	0	0.87×10^6	0.87×10^6

NOTE:

1. Values for this parameter obtained through National Solar Data Network

4.8 System Availability

The availability of a solar energy system is determined by the ability of its functional subsystems to perform their designed tasks when design operational conditions exist.

This may be expressed as

$$\text{Availability} = \frac{\text{Solar Subsystem Equipment Operating Time}}{\text{Demand for Subsystem Time}}$$

where Availability = 100 percent if the Demand Time is zero.

A subsystem is considered unavailable if a demand for its function exists, prevailing conditions meet appropriate prescribed criteria, and the subsystem fails to perform its function. A subsystem is then considered available at all time when it is not unavailable. Availability also indicates the degree to which a subsystem responded to those demands which it was intended to satisfy. Subsystem availability alone rather than total system availability is presented in this report as more than one subsystem could be expected to be operational at the same time and a composite availability factor would confuse the actual conditions of performance. Availability of the Radian solar energy system as presented in this report is represented by the availability of its Energy Collection and Storage Subsystem and the solar portions of both the Space Heating subsystem and Space Cooling subsystem. The monthly availability of the solar portions of these subsystems is presented in Table IV-8.

The Radian energy collection and storage subsystem is considered available except for those times when the following conditions exist:

(1) INCIDENT SOLAR ENERGY (total solar energy incident on the gross collector array) is greater than twenty-five percent of its monthly average,

(2) STORAGE AVERAGE TEMPERATURE (mass-weighted average temperature of the primary storage medium) is less than its maximum allowable value, and

(3) OPERATIONAL INCIDENT ENERGY (solar energy incident on the collector array during the time that the collector loop is active) is less than twenty-five percent of the INCIDENT SOLAR ENERGY.

The average Energy Collection and Storage Subsystem availability for the Radian solar energy system was 56 percent for the period September 1977 through May 1978. This level of availability is attributed to collector array tracking mechanism problems.

The Radian Space Heating subsystem is considered available except for those times when the following conditions exist:

(1) A space cooling demand was encountered as indicated by SPACE HEATING LOAD (sum of the energy supplied by the solar energy system plus the energy supplied by auxiliary sources) and

(2) no solar energy was used to attempt to satisfy the Space Heating load as indicated by HEATING SOLAR ENERGY (amount of solar energy supplied to the space heating subsystem).

A condition of nonavailability is further tested by:

(3) STORAGE AVERAGE TEMPERATURE greater than the minimum usuable value (100°F) for supply to the Space Heating subsystems.

The average Space Heating Subsystem availability for the Radian solar energy system was 75 percent for the period September 1977 through May 1978. During the primary heating season, December 1977, to February 1978, the relatively lower availability is primarily attributable to the lack of sufficient energy in storage caused by the collector tracker malfunction and did not result from failure of the supply pumps or circulation fan.

The Radian Space Cooling subsystem is considered available except for those times when the following conditions exists:

(1) A space cooling demand was encountered as indicated by SPACE COOLING LOAD (sum of the energy supplied by the solar energy system plus the energy supplied by auxiliary sources) and

(2) no solar energy was used to attempt to satisfy the Space Cooling load as indicated by COOLING SOLAR ENERGY (amount of solar energy supplied to the space cooling subsystem).

A condition of nonavailability is further tested by:

(3) STORAGE AVERAGE TEMPERATURE is greater than the minimum usuable value (180°F) for supply to the space cooling subsystem's absorption cycle air conditioning unit.

At no time during this report period did STORAGE AVERAGE TEMPERATURE reach 180°F, thus the Space Cooling Subsystem was never available.

In general, the lack of availability of Radian solar energy subsystems may be attributed primarily to the higher than anticipated repair and maintenance schedule required by the collector tracking mechanism. Continued improvement in availability was noted following the repair of the leak to the storage tank in December 1977, and the resulting improvement in maintenance schedules that resulted in this discovery. No other hardware malfunctions have been reported outside this subsystem.

TABLE IV-8

System Availability by Major Subsystem

Month	Energy Collection and Storage Subsystem (1, 2) Percent	Space Heating Subsystem (1, 2) Percent	Space Cooling Subsystem (1, 2) Percent
Sep 77	40	100	0
Oct 77	70	100	0
Nov 77	Not Reported	Not Reported	Not Reported
Dec 77	60	30	0
Jan 78	75	60	0
Feb 78	80	10	0
Mar 78	70	100	0
Apr 78	55	100	0
May 78	0	100	0
Avg.	56	75	0

NOTE:

1. Monthly percentages rounded to nearest 5 percent

2. Values for this parameter computed from data obtained through National Solar Data Network.

4.9 Energy Savings

Solar energy system savings are realized whenever energy provided by the solar energy system is used to meet heating or cooling demands rather than energy provided by auxiliary fuel sources. For the Radian solar energy system, a one-to-one correlation exists between the solar and conventional equipment providing for a direct comparision between the two sources of meeting building demand. The conventional sources of heating and cooling have been taken to be the baseline systems with savings being realized whenever solar energy could be employed to supplant their use. Since the source of conventional heating is natural gas and conventional air conditioning is electricity, savings of both types of energy may be realized. Measured monthly values of HEATING ELECTRICAL SAVINGS and COOLING ELECTRICAL SAVINGS (the estimated difference between the electrical requirements of the conventional system carrying the full load and the actual electrical energy consumed by the system) and FOSSIL ENERGY SAVINGS (estimated difference between fossil energy requirements of the alternative conventional system carrying the full load and the actual fossil energy consumed by the system) are presented in Table IV-9. The ENERGY COLLECTION AND STORAGE SUBSYSTEM OPERATING ENERGY (electrical energy to support the subsystem, e.g. fans and pumps, not intended to directly effect the thermal state of the subsysstem) is reprinted here from Table IV-7 since this quantity is not included in the subsystem electrical energy savings and must be algebracilly added to obtain the Total Electrical Savings.

The value of 3413 Btu/killowatt hour has been used to convert all electrical energy savings to kilowatt hours and 1000 Btu/cubic feet used to convert the fossil savings to cubic feet.

Comparision of the Total Savings from Table IV-9 with the SPACE HEATING LOAD (the sum of energy supplied by both solar and auxiliary sources) from Table IV-5 shows that positive savings were realized during each month which had a significant heating demand with the exception of December 1977. It appears that during that month the use of solar energy to provide space heating was frequently manually inhibited, because average storage tank temperatures were often in excess of the minimum value of 100°F considered adequate for space heating, yet no solar energy was provided to the space heating subsystem from solar storage. The reason for this is not known, but it was during this month that both the leak of city water into the storage tank was fixed (on the 6th) and the freeze protection heat exchanger was activated (the 22nd) to isolate the collector loop from the storage tank. The largest Total Savings were realized in March 1978 when the combined availability of the energy collection and storage and the heating subsystems were their highest value.

Of the 12 million Btu of heating demand 9.4 million Btu were required during January and February 1978. The savings during those months were 0.7 million Btu and 0.12 million Btu respectively. The lower savings realized in February 1978 may be traced to the unusually poor insolation early in the month and the poor collector tracking performance which ocurred in the latter part of the month.

The algebraic sum of the Total Savings during the report period shows a net of 0.03 million Btu. This extremely small savings has resulted from a combination of several factors, but all may be traced to the poor performance of the collector tracking mechanism which has been the underlying cause of the frequent subsystem unavailability.

TABLE IV-9

Energy Savings

Month	ECSS OPERATING ENERGY, Btu	HEATING ELECTRICAL SAVINGS, Btu	COOLING ELECTRICAL SAVINGS, Btu	HEATING FOSSIL SAVINGS, Btu	TOTAL ELECTRICAL SAVINGS, Btu	TOTAL ELECTRIC SAVINGS kw hr	TOTAL FOSSIL SAVINGS cubic feet	TOTAL SAVINGS, Btu
Sep 77	0.20×10^6	0	0	0	-0.20×10^6	- 60	0	-0.2×10^6
Oct 77	0.32×10^6	0	0	0.02×10^6	-0.32×10^6	- 95	20	-0.3×10^6
Nov 77	*	*	*	*	*	*	*	*
Dec 77	0.28×10^6	0.13×10^6	0	0.08×10^6	-0.15×10^6	- 45	80	-0.7×10^6
Jan 78	0.25×10^6	0.34×10^6	0	0.61×10^6	0.09×10^6	25	610	0.7×10^6
Feb 78	0.27×10^6	0.24×10^6	0	0.15×10^6	-0.03×10^6	- 10	150	0.12×10^6
Mar 78	0.38×10^6	-0.02×10^6	0	1.41×10^6	-0.40×10^6	-120	141	1.01×10^6
Apr 78	0.33×10^6	-0.01×10^6	0	0.46×10^6	-0.34×10^6	-135	460	0.12×10^6
May 78	0	0	0	-0.72×10^6	0	0	-720	-0.72×10^6

* Not Reported

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* Copies of these reports may be obtained from Technical Information Center P. O. Box 62, Oak Ridge, Tenn. 37830

APPENDIX A

DEFINITIONS OF PERFORMANCE FACTORS

COLLECTOR ARRAY PERFORMANCE

The collector array performance is characterized by the amount of solar energy collected with respect to the energy available to be collected.

- INCIDENT SOLAR ENERGY is the total solar energy incident on the gross collector array area. This is the area of the collector array energy-receiving aperture, including the framework which is an integral part of the collector structure.

- OPERATIONAL INCIDENT ENERGY is the amount of solar energy incident on the collector array during the time that the collector loop is active (attempting to collect energy).

- COLLECTED SOLAR ENERGY is the thermal energy removed from the collector array by the energy transport medium.

- COLLECTOR ARRAY EFFICIENCY is the ratio of the energy collected to the total solar energy incident on the collector array. It should be emphasized that this efficiency factor is for the collector array, and available energy includes the energy incident on the array when the collector loop is inactive. This efficiency must not be confused with the more common collector efficiency figures which are determined from instantaneous test data obtained during steady state operation of a single collector unit. These efficiency figures are often provided by collector manufacturers or presented in technical journals to characterize the functional capability of a particular collector design. In general, the collector panel maximum efficiency factor will be significantly higher than the collector array efficiency reported here.

STORAGE PERFORMANCE

The storage performance is characterized by the relationships among the ENERGY TO STORAGE, ENERGY FROM STORAGE, and the subsequent CHANGE IN STORED ENERGY.

- ENERGY TO STORAGE is the amount of energy, both solar and auxiliary, delivered to the primary storage medium.

- ENERGY FROM STORAGE is the amount of energy extracted by the load subsystems from the primary storage medium.

- CHANGE IN STORED ENERGY is the difference in the estimated stored energy during the specified reporting period, as indicated by the relative temperature of the storage medium (either positive or negative value).

- o STORAGE AVERAGE TEMPERATURE is the mass-weighted average temperature of the primary storage medium.

- o STORAGE EFFICIENCY is the ratio of the sum of the energy removed from storage and the change in stored energy to the energy delivered to storage.

ENERGY COLLECTION AND STORAGE SUBSYSTEM

The Energy Collection and Storage Subsystem (ECSS) is composed of the collector array, the primary storage medium, the transport loops between these, and other components in the system design which are necessary to mechanize the collector and storage equipment.

- o INCIDENT SOLAR ENERGY is the total solar energy incident on the gross collector array area. This is the area of the collector array energy-removing aperture, including the framework which is an integral part of the collector structure.

- o AMBIENT TEMPERATURE is the average temperature of the outdoor environment at the site.

- o ENERGY TO LOADS is the total thermal energy transported from the ECSS to all load subsystems.

- o ECSS OPERATING ENERGY is the electrical operating energy required to support the ECSS heat transfer loops.

SPACE HEATING SUBSYSTEM

The space heating subsystem is characterized by performance factors accounting for the complete energy flow into the subsystem. The average building temperature and the average ambient temperature are tabulated to indicate the relative performance of the subsystem in satisfying the space heating load and in controlling the temperature of the conditioned space.

- o SPACE HEATING LOAD is the sum of the energy supplied by the solar energy system plus the energy supplied by auxiliary sources.

- o SOLAR FRACTION OF LOAD is the percentage of the total demand which is supported by solar energy.

- o SOLAR ENERGY USED is the amount of solar energy supplied to the space heating subsystem.

- o OPERATING ENERGY is the amount of electrical energy required to support the subsystem, (e.g., fans, pumps, etc.) and which is not intended to affect directly the thermal state of the subsystem.

- o AUXILIARY THERMAL USED is the amount of energy supplied to the major components of the subsystem in the form of thermal

energy in a heat transfer fluid or its equivalent. This term also includes the converted electrical and fossil fuel energy supplied to the subsystem.

- o AUXILIARY FOSSIL FUEL is the amount of fossil fuel energy supplied directly to the subsystem.

- o ELECTRICAL ENERGY SAVINGS is the estimated difference between the electrical energy requirements of an alternative conventional system (carrying the full load) and the actual electrical energy required by the subsystem.

- o FOSSIL ENERGY SAVINGS is the estimated difference between the fossil energy requirements of the alternative conventional system (carrying the full load) and the actual fossil energy requirements of the subsystem.

- o BUILDING TEMPERATURE is the average heated space dry bulb temperature.

- o AMBIENT TEMPERATURE is the average ambient dry bulb temperature at the site.

SPACE COOLING SUBSYSTEM

The space cooling subsystem is characterized by performance factors similar to those of the space heating subsystem described previously.

- o SPACE COOLING LOAD is the total energy, including sensible and latent, removed from the air in the spaced-cooled area of the building.

- o SOLAR FRACTION OF LOAD is the percentage of the demand which is supported by solar energy.

- o SOLAR ENERGY USED is the amount of solar energy supplied to the space-cooling subsystem.

- o OPERATING ENERGY is the amount of electrical energy required to support the subsystem, (e.g., fans, pumps, etc.) and which is not intended to affect directly the thermal state of the subsystem.

- o AUXILIARY THERMAL USED is the amount of energy supplied to the major components of the subsystem in the form of thermal energy in a heat transfer fluid, or its equivalent. This term also includes the converted electrical and fossil fuel supplied to the subsystem.

- <u>AUXILIARY ELECTRIC FUEL</u> is the amount of electrical energy supplied directly to the subsystem

- <u>ELECTRICAL ENERGY SAVINGS</u> is the estimated difference between the electrical energy requirements of an alternative conventional system (carrying the full load) and the actual electrical energy required by the subsystem.

APPENDIX B

SOLAR ENERGY SYSTEM PERFORMANCE EQUATIONS FOR RADIAN CORPORATION

I. INTRODUCTION

Solar energy system performance is evaluated by performing energy balance calculations on the system and its major subsystems. These calculations are based on physical measurement data taken from each subsystem every 320 seconds. This data is then numerically combined to determine the hourly, daily, and monthly performance of the system. This appendix describes the general computational methods and the specific energy balance equations used for this evaluation.

Data samples from the system measurements are numerically integrated to provide discrete approximations of the continuous functions which characterize the system's dynamic behavior. This numerical integration is performed by summation of the product of the measured rate of the appropriate performance parameters and the sampling interval over the total time period of interest.

There are several general forms of numerical integration equations which are applied to each site. These general forms are exemplified as follows: The total solar energy available to the collector array is given by

$$\text{SOLAR ENERGY AVAILABLE} = (1/60) \sum [\text{I001} \times \text{AREA}] \times \Delta\tau$$

Where I001 is the solar radiation measurement provided by the pyranometer in BTU/ft^2-hr, AREA is the area of the collector array in square feet, $\Delta\tau$ is the sampling interval in minutes, and the factor (1/60 is included to correct the solar radiation "rate" to the proper units of time.

Similarly, the energy flow within a system is given typically by

$$\text{COLLECTED SOLAR ENERGY} = \sum [\text{W100} \times \text{CP} \times \text{RHO} \times (\text{T150} - \text{T100})] \times \Delta\tau$$

Where W100 is the flow rate of the heat transfer fluid in gal/min, CP and RHO are the specific heat and density, and T100 and T150 are the temperatures of the fluid before and after passing through the heat exchanging component. Frequently this temperature difference is referred to as simply TD100. The product W100 x CP x RHO is often combined and represented as M100.

For electrical power, a general example is

$$\text{ECSS OPERATING ENERGY} = (3413/60) \sum [\text{EP100}] \times \Delta\tau$$

where EP100 is the power required by electrical equipment in kilowatts and the two factors (1/60) and (3413) correct the data to Btu/min.

These equations are comparable to those specified in "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program". This document, given in the list of references [14] was prepared by an inter-agency committee of the government, and presents guidelines for thermal performance evaluation.

Performance factors are computed for each hour of operation of systems. Each numerical integration process, therefore, is performed over a period of one hour. Since long-term performance data is desired, it is necessary to build these hourly performance factors to daily values. This is accomplished, for energy parameters, by summing the twenty-four hourly values. For temperatures, the hourly values are averaged. Certain special factors, such as efficiencies, require appropriate handling to properly weight each hourly sample for the daily value computation. Similar procedures are required to convert daily values to monthly values.

The equations presented for the calculation of performance factors for specific sites conform to the general guidelines outlined above. Additional consideration include special handling of calculations to account for various modes of operation of systems. That is, some components and sensors are incorporated into systems so that they are shared by more than one subsystem, and consequently the energy flow associated with them must be accounted to appropriate subsystems based on system mode of operation.

Modes of operation are defined for all solar energy systems. These modes are used to assist in apportioning the energy provided to or consumed by a subsystem so that the usefulness of that subsystem may be evaluated. Notes following various equations in this Appendix are intended to indicate the system's operating mode. These modes reflect the unique operating aspects of the particular solar energy system. Table B-1 summarizes the primary modes to be encountered in the Radian solar energy system.

TABLE B-1 System Operating Modes

Mode No.	Description
1	Energy collection and storage
2	Solar heating
3	Solar cooling
4	Auxiliary heating
5	Auxiliary cooling
6	Solar + Auxiliary heating
7	Solar + Auxiliary cooling

EQUATIONS USED IN MONTHLY PERFORMANCE REPORT

NOTE: - ALL UNITS BTU UNLESS OTHERWISE SPECIFIED

- MEASUREMENT NUMBERS REFERENCE SYSTEM SCHEMATIC FIGURES III-1 AND III-2

SITE SUMMARY REPORT

INCIDENT SOLAR ENERGY

$$= (1/60) \sum [I001 \times AREA] \times \Delta\tau$$

INCIDENT SOLAR ENERGY PER UNIT AREA (BTU/SQ. FT)

$$= 1/60 \sum I001 \times \Delta\tau$$

COLLECTED SOLAR ENERGY

$$= \sum [M100 \times CP \times (T150 - T100)] \times \Delta\tau$$

COLLECTED SOLAR ENERGY PER UNIT AREA (BTU/SQ. FT.)

$$= \sum [M100 \times CP \times (T150 - T100)/AREA] \times \Delta\tau$$

AVERAGE AMBIENT TEMPERATURE (DEGREES F)

$$= (1/60) \sum [T001] \times \Delta\tau$$

AVERAGE BUILDING TEMPERATURE (DEGREES F)

$$= (1/60) \sum [T601] \times \Delta\tau$$

ECSS SOLAR CONVERSION EFFICIENTY

= SOLAR ENERGY TO LOAD/INCIDENT SOLAR ENERGY

ECSS OPERATING ENERGY

$$= (56.88) \sum (EP101) \times \Delta\tau$$

WHENEVER COLLECTORS ARE OPERATING

TOTAL SYSTEM OPERATING ENERGY

= ECSS OPERATING ENERGY + HEATING OPERATING ENERGY + COOLING OPERATING ENERGY

TOTAL ENERGY CONSUMED

= AUXILIARY ENERGY + SYSTEM OPERATING ENERGY + SOLAR ENERGY COLLECTED

LOAD SUBSYSTEM SUMMARY:

HEATING LOAD = HEATING SOLAR ENERGY + HEATING AUXILIARY THERMAL ENERGY

COOLING LOAD = (COOLING AUXILIARY ELECTRIC ENERGY) x COP + (COOLING SOLAR ENERGY) x COPS

where COP is the coefficient of performance of the auxiliary air conditioner

and COPS is the coefficient of performance of the solar air conditioner

SYSTEM LOAD = HEATING LOAD + COOLING LOAD

HEATING SOLAR FRACTION (PERCENT)

= 100 x (HEATING SOLAR ENERGY/HEATING LOAD)

COOLING SOLAR FRACTION (PERCENT)

= 100 x (SOLAR AIR CONDITIONER LOAD/COOLING LOAD)

SOLAR ENERGY USED:

HEATING SOLAR ENERGY

$$= [M401 \times CP \times (T401 - T451)] \times \Delta\tau$$

whenever in MODE 2 OR 6

COOLING SOLAR ENERGY

$$= [M401 \times CP \times (T401 - T451)] \times \Delta\tau$$

whenever in MODES 3 OR 7

TOTAL SOLAR ENERGY TO LOADS

$$= [M401 \times CP \times (T401 - T451)] \times \Delta\tau$$

AVERAGE BUILDING TEMPERATURE (DEGREES F)

$= (1/60) \sum [T601] \times \Delta\tau$

ECSS SOLAR CONVERSION EFFICIENCY

= SOLAR ENERGY TO LOAD/INCIDENT SOLAR ENERGY

ECSS OPERATING ENERGY

$= (56.88) \sum (EP101) \times \Delta\tau$

WHENEVER COLLECTORS ARE OPERATING

TOTAL SYSTEM OPERATING ENERGY

= ECSS OPERATING ENERGY + HEATING OPERATING ENERGY + COOLING OPERATING ENERGY

TOTAL ENERGY CONSUMED

= AUXILIARY ENERGY + SYSTEM OPERATING ENERGY + SOLAR ENERGY COLLECTED

LOAD SUBSYSTEM SUMMARY:

HEATING LOAD = HEATING SOLAR ENERGY + HEATING AUXILIARY THERMAL ENERGY

COOLING LOAD = (COOLING AUXILIARY ELECTRIC ENERGY) x COP + (COOLING SOLAR ENERGY) x COPS

where COP is the coefficient of performance of the auxiliary air conditioner

and COPS is the coefficient of performance of the solar air conditioner

SYSTEM LOAD = HEATING LOAD + COOLING LOAD

HEATING ELECTRICAL SAVINGS

= AUXILIARY HEATING OPERATING ENERGY - SOLAR HEATING OPERATING ENERGY

COOLING ELECTRICAL SAVINGS

= AUXILIARY ELECTRIC ENERGY - COOLING SOLAR ENERGY

TOTAL ELECTRICAL SAVINGS

= HEATING ELECTRICAL SAVINGS + COOLING ELECTRICAL SAVINGS - ECSS OPERATING ENERGY

HEATING FOSSIL SAVINGS

= (HEATING LOAD/CEEH) - HEATING AUXILIARY FUEL

where CEEH is the auxiliary burner efficiency

TOTAL FOSSIL SAVINGS

= HEATING FOSSIL SAVINGS

SYSTEM PERFORMANCE FACTOR

= SYSTEM LOAD/[AUXILIARY FOSSIL FUEL + 3.33 x (AUXILIARY ELECTRIC FUEL + SYSTEM OPERATING ENERGY)]

OPERATIONAL INCIDENT ENERGY

$$= 1/60 \sum [I001 \times AREA] \times \Delta\tau$$

whenever collector pump is running

COLLECTOR ARRAY EFFICIENTY

= SOLAR ENERGY COLLECTED/INCIDENT SOLAR ENERGY

ENERGY TO STORAGE

$$= \sum [M100 \times CP \times (T101 - T151)] \times \Delta\tau$$

ENERGY FROM STORAGE

$$= \sum [M400 \times CP \times (T400 - T450)] \times \Delta\tau$$

CHANGE IN STORED ENERGY

= STORAGE CAPACITY x [HEAT CONTENT PREVIOUS SCAN - HEAT CONTENT PRESENT SCAN]

where storage capacity is the active volume of the tank

STORAGE AVERAGE TEMP (DEGREE F)

$$= 1/60 \sum [(T200 + T201 + T202) / 3] \times \Delta\tau$$

STORAGE EFFICIENCY

= (CHANGE IN STORED ENERGY + ENERGY FROM STORAGE) / ENERGY TO STORAGE

ECSS SOLAR CONVERSION EFFICIENCY

= SOLAR ENERGY TO LOAD / INCIDENT SOLAR ENERGY

DIFFUSE INSOLATION (BTU/SQ. FT.)

$= (1/60) \sum [I002] \times \Delta\tau$

DAYTIME AMBIENT TEMP (DEGREE F)

$= (1/360) \sum [T001] \times \Delta\tau$

$\pm$ 3 HOURS FROM SOLAR NOON

RELATIVE HUMIDITY (PERCENT)

$= (1/60) \sum [RH005] \times \Delta\tau$

WIND DIRECTION (DEGREES)

$= (1/60) \sum [D001] \times \Delta\tau$

WIND SPEED (M.P.H.)

$= (1/60) \sum [V001] \times \Delta\tau$

OPERATING ENERGY (BTU):

HEATING OPERATING ENERGY

$= (56.88) \sum (EP401 + EP501) \times \Delta\tau$

for mode 2

$= (56.88) \sum [EP502] \times \Delta\tau$

for modes 4 and 7

COOLING OPERATING ENERGY

$= (56.88) \sum (EP401 + EP501) \times \Delta\tau$

for modes 3, 5, 7

TOTAL OPERATING ENERGY

= ECSS OPERATING ENERGY + HEATING OPERATING ENERGY + COOLING OPERATING ENERGY

HEATING AUXILIARY THERMAL ENERGY

$$= CF \times CEEF \times (F400 - LF400)$$

WHERE CF IS THE HEAT CONTENT OF THE FOSSIL FUEL

TOTAL AUXILIARY THERMAL ENERGY

= HEATING AUXILIARY THERMAL ENERGY

COOLING AUXILIARY ELECTRIC FUEL

$$= (56.88) \sum [EP502] \times \Delta\tau$$

TOTAL AUXILIARY ELECTRIC FUEL

= COOLING AUXILIARY ELECTRIC FUEL

HEATING AUXILIARY FOSSIL FUEL

$$= CF \times (F400 - LF400)$$

TOTAL AUXILIARY FOSSIL FUEL

= HEATING AUXILIARY FOSSIL FUEL

APPENDIX C

Collector Array Analysis for Radian, Inc. Solar Energy System, Austin, Texas

An analysis of the effect of phenomena actually encountered by the Radian system collector array was performed for measurement data taken from the period December 1, 1977 to mid-March, 1978. The analysis technique used is an extension of the procedures recommended by ASHRAE Standard 93-77 [17]. Modifications were made to the ASHRAE procedure to allow evaluation of performance for two sub-sets of the measurement data. These sub-sets were:

1. selected data based on steady-state conditions which meet the ASHRAE testing requirements, and

2. selected data based on degree of transient behavior (i.e., - on amount of variation from steady-state opertion).

This technique is important for the evaluation of how installed solar energy collector subsystems perform as compared to how they performed in the "test stand" environment. Actual conditions of all-day system operation differ greatly from the testing standards. Effects of these conditions can be eliminated by performance evaluation using only that data which meet the steady-state testing criteria. Once sufficient data are available for this comparison (field installation versus test environment for steady-state data) and an evaluation is completed, the second step is to allow relaxation of the criteria limits to evaluate how the actual transient variation in meterological conditions affect the collector's performance. To evaluate real effects of actual installation requires real meterological conditions. These conditions do not necessarily provide, in short periods of time, the specific range and composition of parametric characteristics needed for proper evaluation of collector performance. Thus, the continual, long term monitoring of many solar energy systems by the National Solar Data Program is extremely beneficial in evaluations of this nature.

To meet the "steady-state" requirements of ASHRAE 93-77, constraints must be placed on the field-derived data. The constraints are characterized by limitations on magnitude and/or limitations on allowable variations with time. The eight constraints used in this study are applied to: sun angle, solar radiation, solar radiation variation between data samples, wind velocity, collector array inlet temperature variations between data samples, temperature gain across the collector array, variations between data samples, ambient temperature variation between data samples, and flowrate through the collector array variations between data samples.

The conditions used for "steady-state" evaluation were: sun angle within 30 degrees of normal to the collector surface, solar radiation greater than 200 Btu/ft^2 hr, wind velocity less than 10 miles per hour and less than 5 percent variation between data samples. Further discussion of this analytical approach may be found in Reference 18.

Evaluation results of the Radian collector array analysis are presented in Figures C-1 through C-3. In Figure C-1, all data points which passed the "steady-state" requirements (except for limitation of maximum wind speed) are presented to show how data from actual conditions exhibit a degree of scatter not generally found under testing conditions.

Application of the wind speed constraint of a maximum allowable value of 10 miles per hour causes a noticable reduction in the data scatter. Figure C-2 shows the bounded regions of data for maximum wind speeds of 10 and 20 miles per hour with all other constraints held to their "steady-state" values. This reduction illustrates the negative impact of wind on the Radian collector array for the test period. Similar evaluations on the effect of the relaxation of each of the other constraints did not produce significant changes in performance. The inference from this is not necessarily that the collector array performance would not be sensitive to these "non-test standard" conditions - but rather that during this test period these conditions did not occur in such magnitude as to impact overall performance.

An additional evaluation was made with the data to determine effect of time of day on the collector array performance. As indicated in Figure C-3, the array exhibits markedly poorer than average performance in the afternoon. The cause of this degraded performance is not known, but is suspected to be attributable to the problems with the tracking mechanism's pointing accuracy.

In conclusion, evaluation of the collector array at Radian shows that wind speed has a noticeable effect, that collector efficiency is markedly higher in the morning hours and that this particular array has losses from the collectors being somewhat higher than expected based on collector manufacturer data.

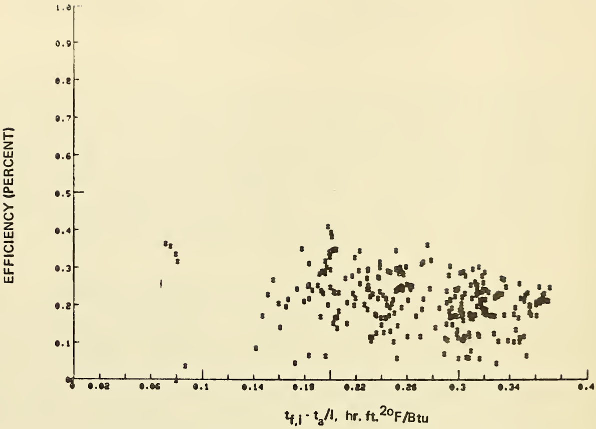

Figure C-1. Collector Performance for the Radian Solar Energy System

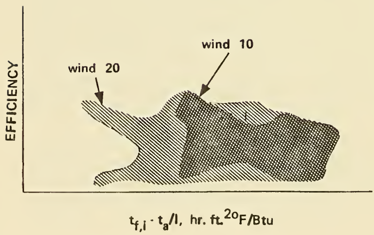

Figure C-2. Wind Effect

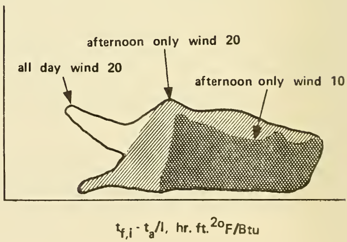

Figure C-3. Time of Day Effect

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